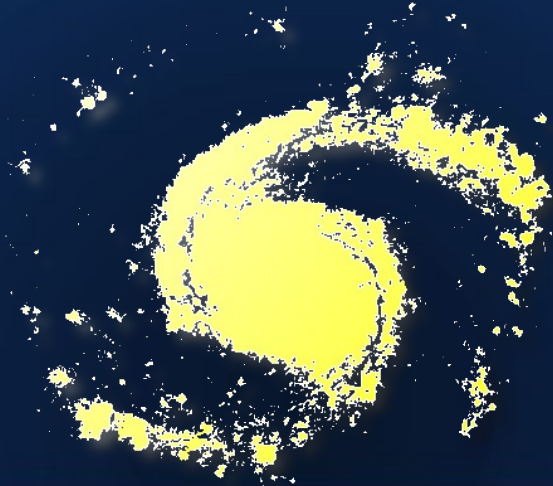


Galaxy Formation Modeling/Decaying Dark Matter

Andrew Benson

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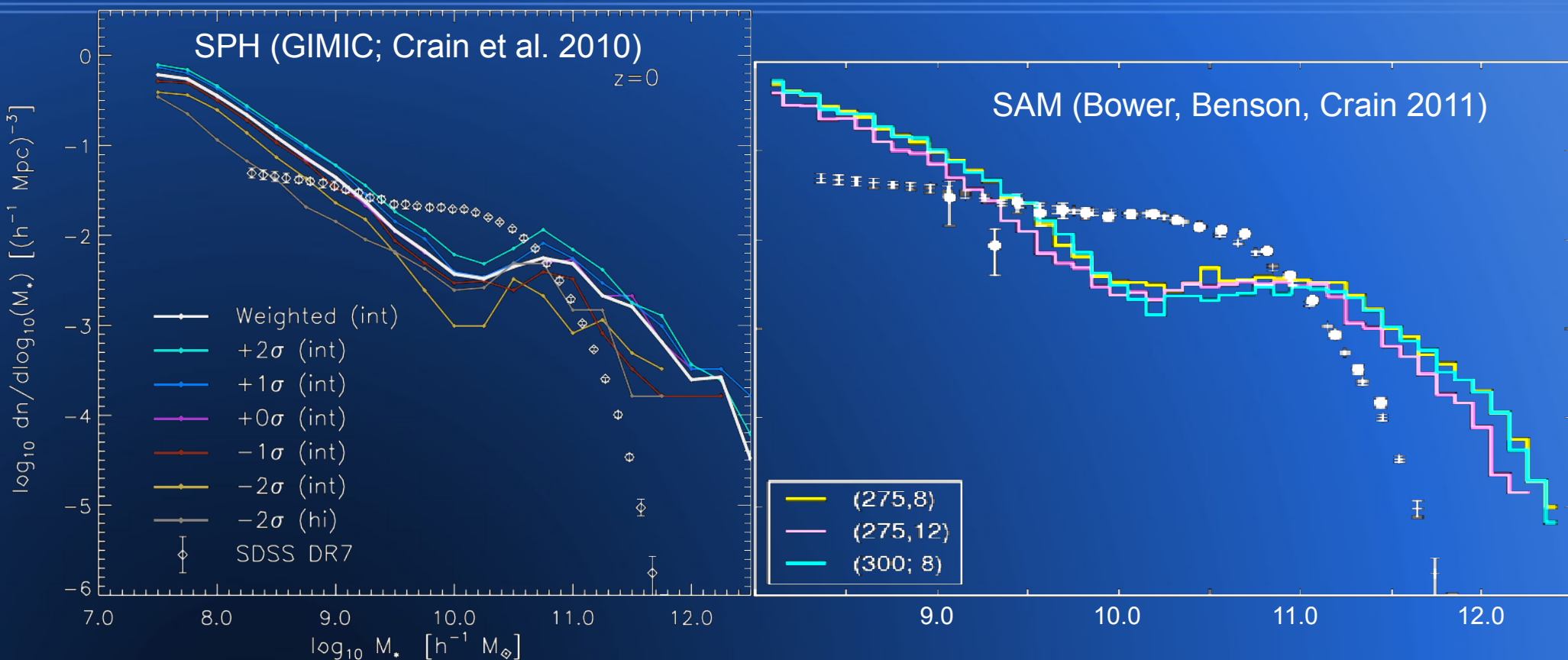
Galaxy Formation Modeling

Introduction | Models | Design | Applications | Decaying Dark Matter | Local Group | Constraints | Summary

- What's the point?
 - Rapid exploration of physical models/parameter spaces
 - Statistical results in excellent agreement with hydrodynamical simulations

SPH vs. SAM Stellar Mass Functions

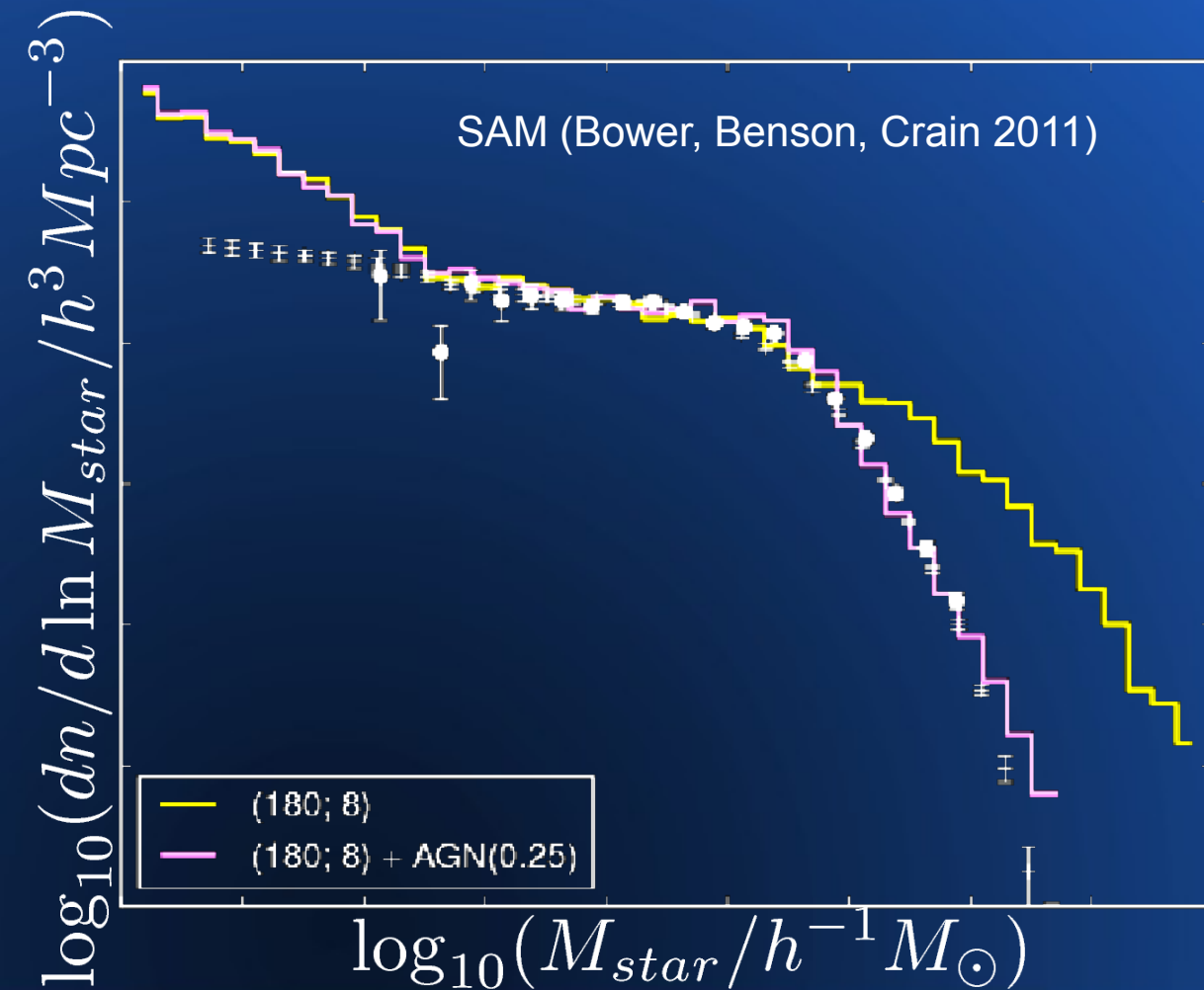
Introduction | Models | Design | Applications | Decaying Dark Matter | Local Group | Constraints | Summary



- Two methods produce near identical results...
- ...when assumptions are matched

Using SAM To Predict SPH

Introduction | Models | Design | Applications | Decaying Dark Matter | Local Group | Constraints | Summary



- With matched physics can explore parameter space
- Or add new physics, e.g. AGN feedback
- Predict SPH results

Galaxy Formation Modeling

Introduction | **Models** | Design | Applications | Decaying Dark Matter | Local Group | Constraints | Summary

- What's the point?
 - Rapid exploration of physical models/parameter spaces
 - Statistical results in excellent agreement with hydrodynamical simulations
- Goals?
 - Predictive power to test theoretical understanding
 - Facilitate insights into the physics

Advancing Galaxy Formation Codes

Introduction | **Models** | Design | Applications | Decaying Dark Matter | Local Group | Constraints | Summary

- Why a new code?



- How?
 - Adding in new features (e.g. self-consistent reionisation, noninstantaneous recycling, new star formation rules) and existing models can be
 - sites.google.com/site/galacticusmodel
 - Create a code which is modular by design, isolating assumptions so that they don't have consequences throughout the code.


Design Features

Introduction | Models | **Design** | Applications | Decaying Dark Matter | Local Group | Constraints | Summary

- Open source (compiles with GNU compilers)
- Modular design
 - Each function can have multiple implementations, selected by input parameter.
 - “Node” can have arbitrary number of components (e.g. DM halo, disk, spheroid), all with multiple implementations
- Combination of smooth (ODE) evolution and instantaneous events (e.g. mergers)

Design Features

Introduction | Models | **Design** | Applications | Decaying Dark Matter | Local Group | Constraints | Summary

- Well documented
 - Promotes a standard format for merger tree data
 - galacticus.uchicago.edu/galacticus/MergerTree文件格式.pdf
 - Parallelized
 - OpenMPI
- 

Source code
Binaries
Cloud (Amazon EC2)
- MPI (soon...)
 - Currently simple, but allows for expansion

External Tools

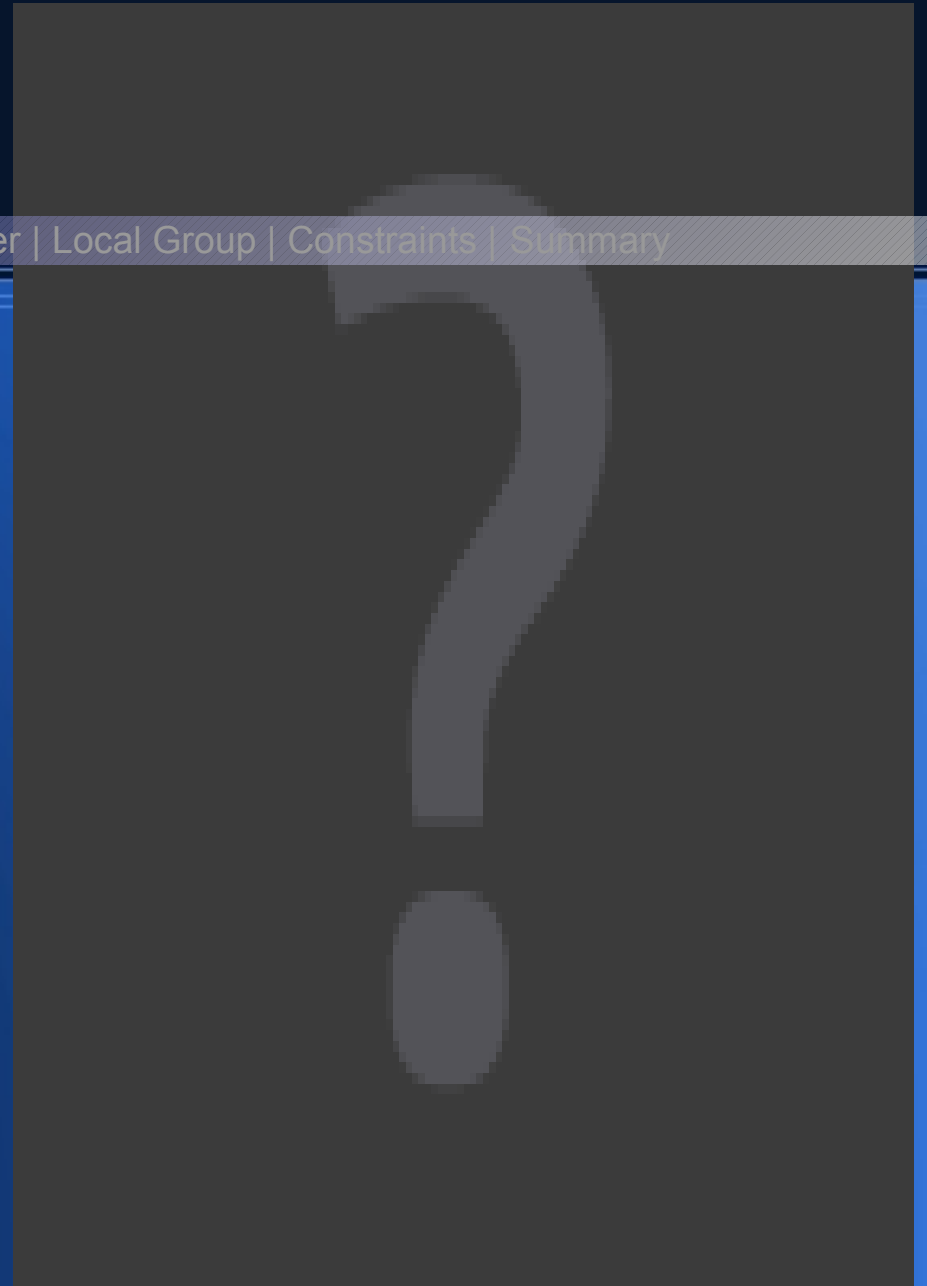
Introduction | Models | **Design** | Applications | Decaying Dark Matter | Local Group | Constraints | Summary

- GNU Scientific Library/FGSL
 - ODE solver; integration; other numerics
- F₀X library
 - Read/write XML files
- FSPS
 - Population synthesis
- Cloudy
 - Cooling times

Node Evolution

Introduction | Models | **Design** | Applications | Decaying Dark Matter | Local Group | Constraints | Summary

- Repeatedly evolved forward—find nodes that to
- Stops when no more evolve:
 - Cannot evolve if have children
 - Can't evolve beyond their satellites
 - Limit on timestep
 - Arbitrary other factors can be included



Advantages

- Modularity makes it highly flexible:
 - Add new star formation rule in 5 minutes
 - Change in cooling model confined to few modules which compute cooling time and rate
- Unified ODE solver makes new features simple:
 - Timestepping handled automatically
 - No need for analytic solutions
 - Implemented noninstantaneous recycling in one afternoon rather than two months!

Disadvantages

- Slower
 - Wasn't designed for speed, but for simplicity
- Missing features (plan
 - Ram pressure/tidal
 - Self-consistent reionization
 - Satellite orbits/disk heating
 - etc.

ICM heating/X-ray emission
Multi-level hierarchy
Black hole merging timescales/kicks
~~H₂-based star formation~~
Resolved disks
Compton/H₂-cooling
Deterministic spins/concentrations

Current Feature List

Introduction | Models | **Design** | Applications | Decaying Dark Matter | Local Group | Constraints | Summary

- Components

- DM profile
[isothermal/
NFW]
- Hot halo
- Disk
[exponential]
- Spheroid
[Hernquist]
- Black holes



Tracks mass and spin.
Spin from mergers and accretion.
Accretion spin-up using Benson & Babul formula
Jet power from Benson & Babul also.

Current Feature List

Introduction | Models | **Design** | Applications | Decaying Dark Matter | Local Group | Constraints | Summary

- Physics
 - Monte-Carlo (PCH method)/N-body merger trees
 - CIE atomic cooling
 - Dynamical friction
 - Star formation/feedback
 - Galaxy merging
 - Adiabatic contraction/sizes
 - Chemical enrichment (instant or non-instant)

Current Feature List

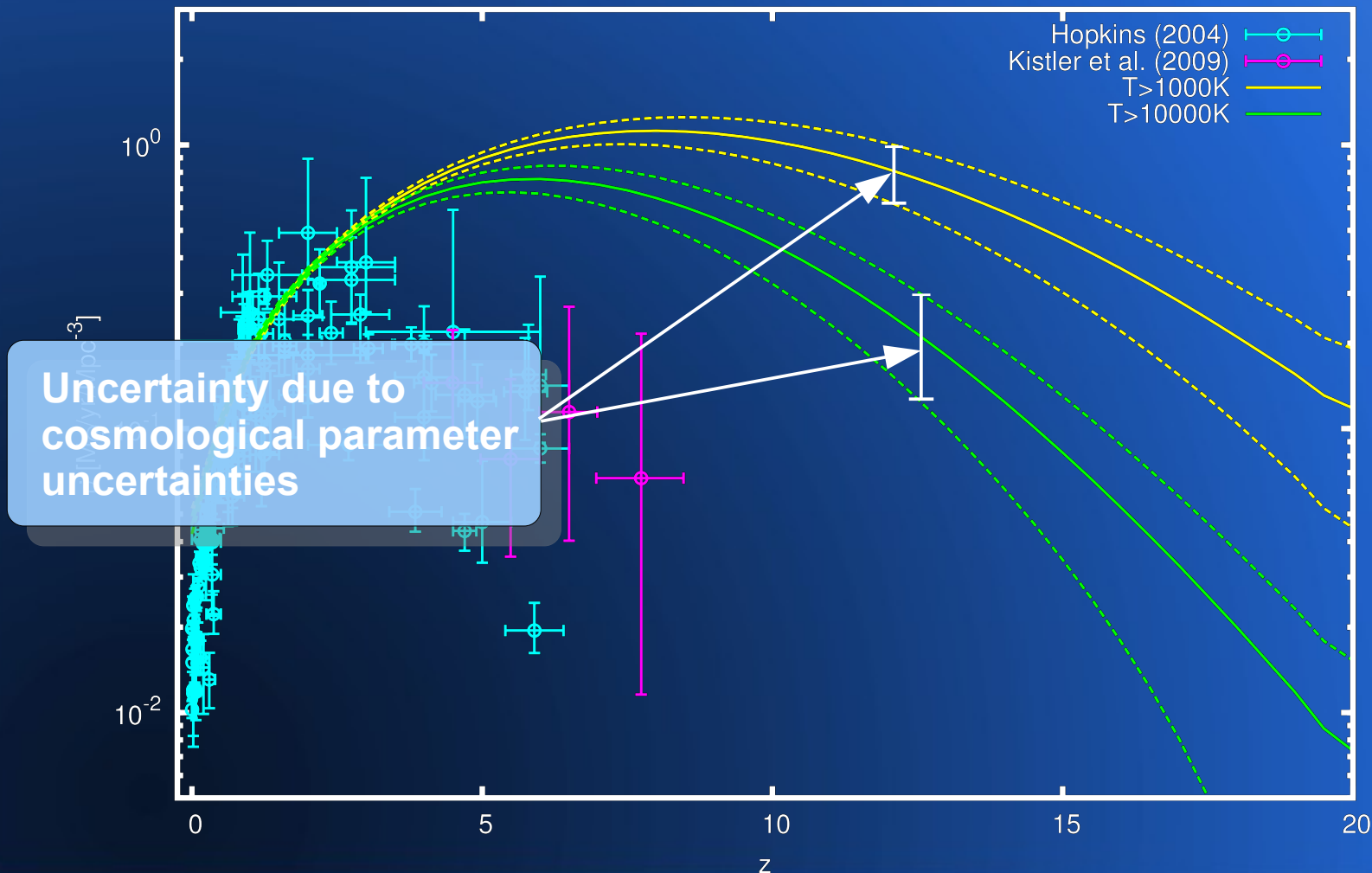
Introduction | Models | **Design** | Applications | Decaying Dark Matter | Local Group | Constraints | Summary

- Physics (*cont.*):
 - Disk instabilities
 - Black hole merging
 - AGN feedback
 - Stellar population synthesis (with arbitrary IMF)

Applications: First Galaxies

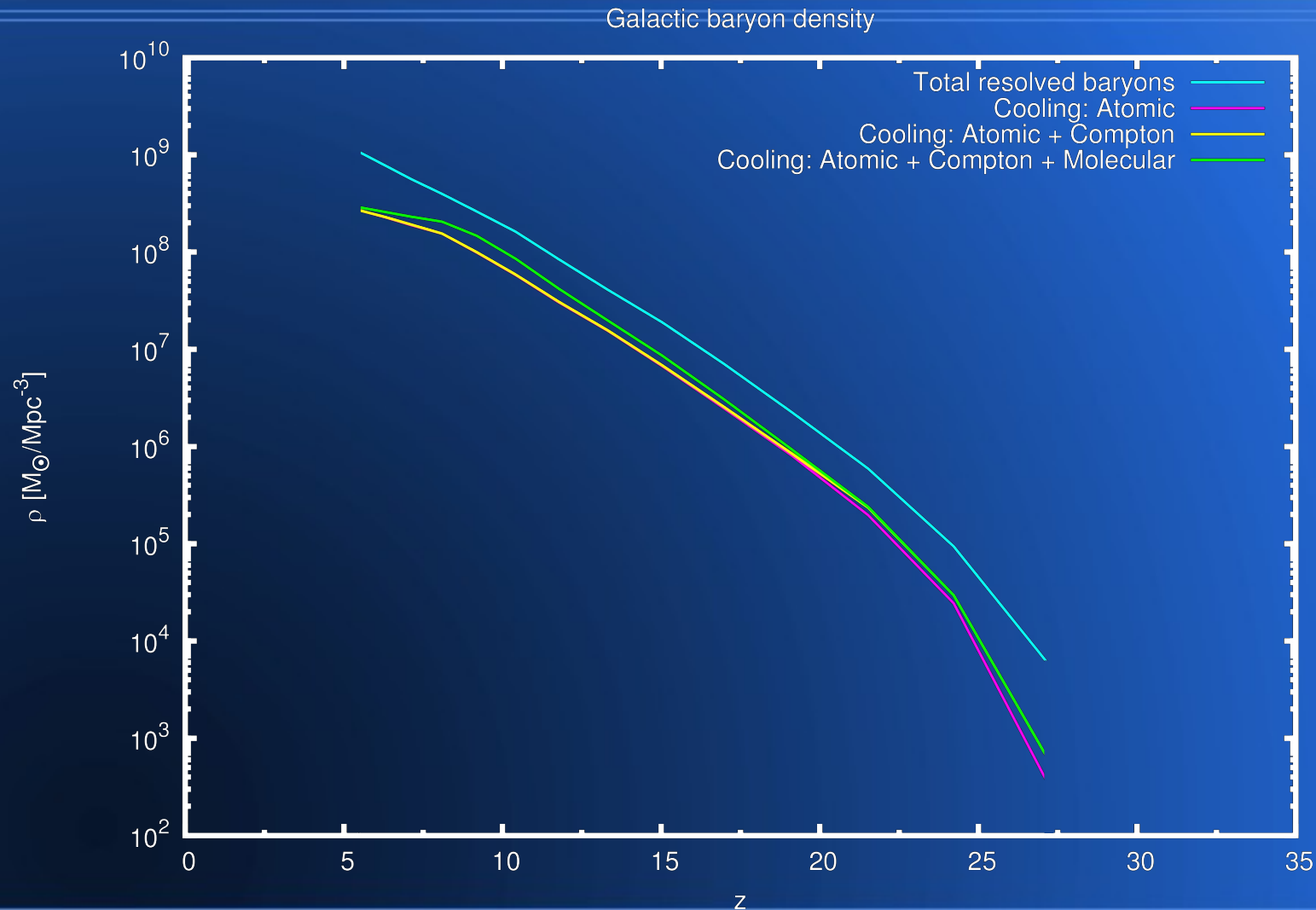
Introduction | Models | Design | **Applications** | Decaying Dark Matter | Local Group | Constraints | Summary

Growth rate of baryons in proto-galactic halos



Applications: First Galaxies

Introduction | Models | Design | **Applications** | Decaying Dark Matter | Local Group | Constraints | Summary



Dark Matter and Galaxies

Introduction | Models | Design | Applications | **Decaying Dark Matter** | Local Group | Constraints | Summary

- Very strong evidence that Universe contains ~85% of mass in some dark form
- Crucial for process of galaxy formation
- Cold Dark Matter (CDM) model very successful
- Canonical model is massive, non-interacting particle with no interesting phenomenology
- But, wide range of possible models still consistent with data.....

Dark Matter and Galaxies

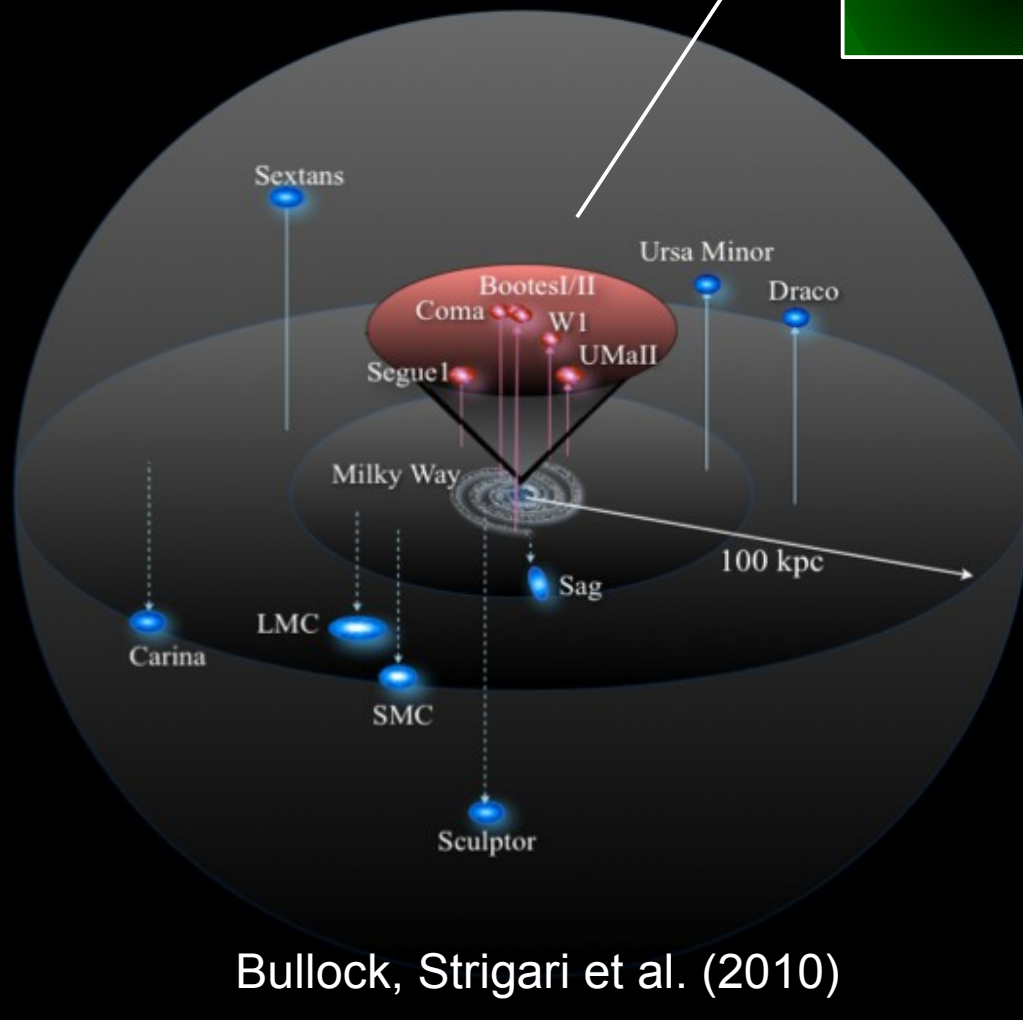
Introduction | Models | Design | Applications | **Decaying Dark Matter** | Local Group | Constraints | Summary

- Direct and indirect detection of dark matter particle is the ultimate goal
- What can we figure out before that happens?
- Astrophysical constraints:
 - Potentially very powerful
 - Difficult systematic (messy astrophysical processes)
 - Where should we look?

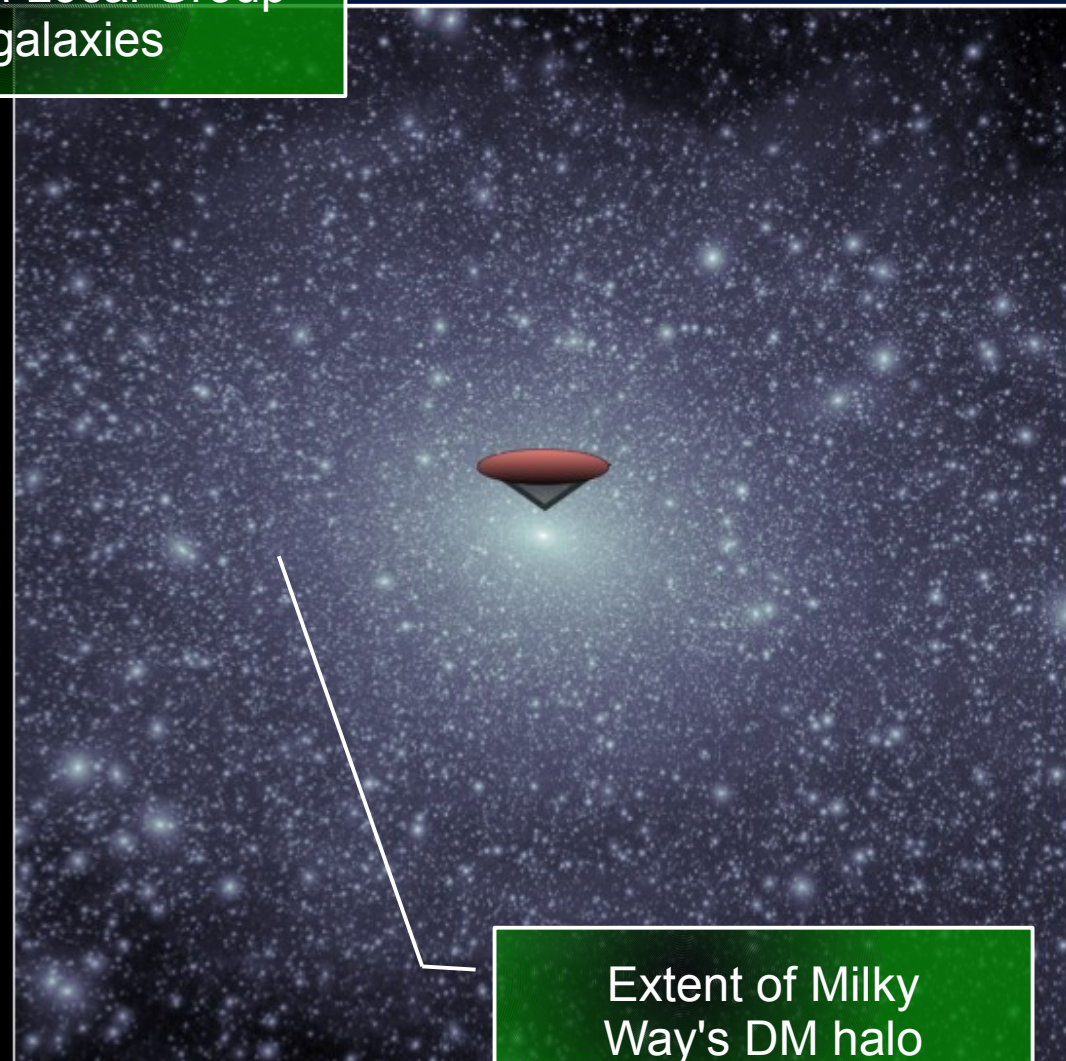
Our Local Group of Galaxies

Introduction | Models | Design | Applications | Decaying Dark Matter | Local Group | Constraints | Summary

Known Local Group galaxies



Bullock, Strigari et al. (2010)



Extent of Milky Way's DM halo

Introduction | Models | Design | Applications | Decaying Dark Matter | **Local Group** | Constraints | Summary

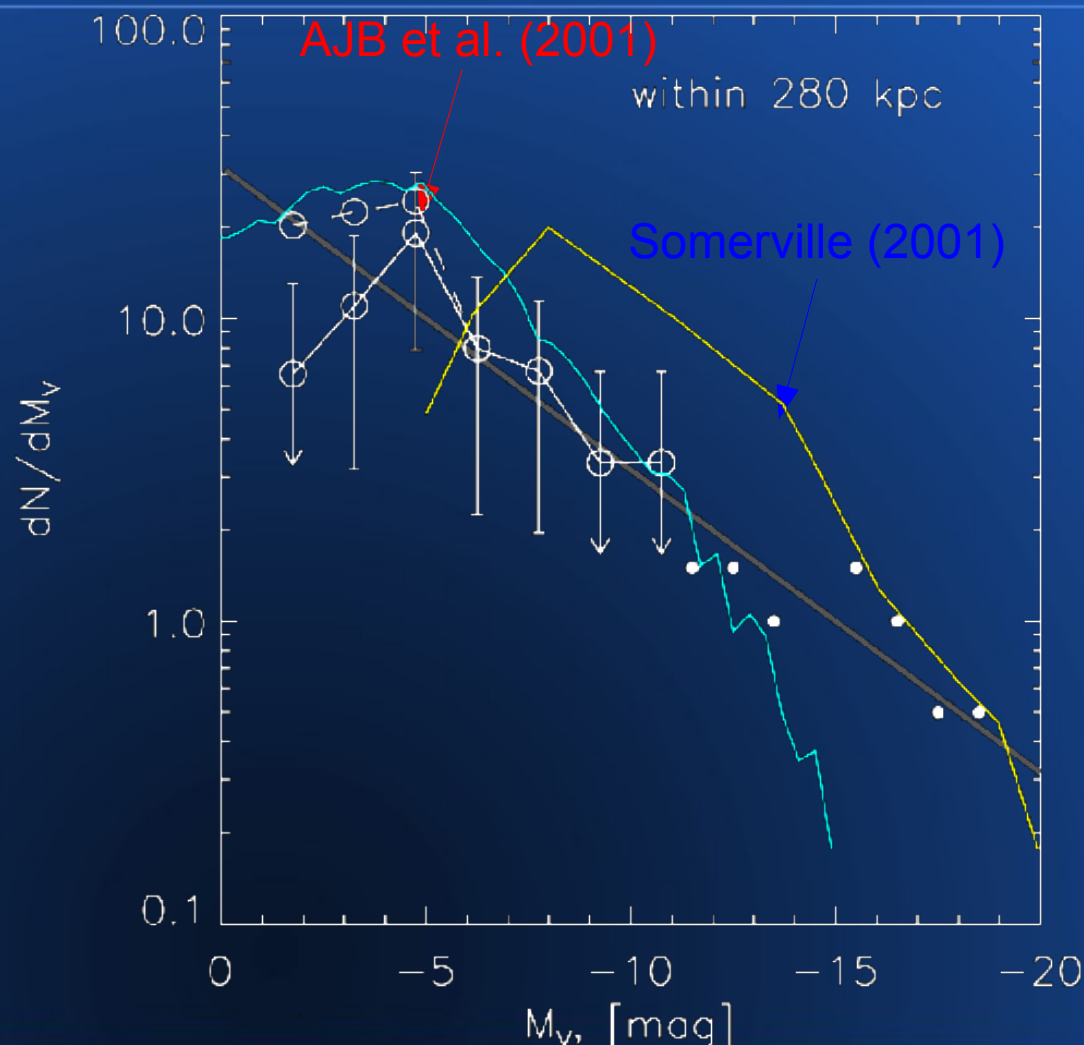
Mass-to-Light Ratios

Introduction | Models | Design | Applications | **Dwarf Galaxies** | Local Group | Constraints | Summary



Local Group Luminosity Function

Introduction | Models | Design | Applications | Decaying Dark Matter | **Local Group** | Constraints | Summary



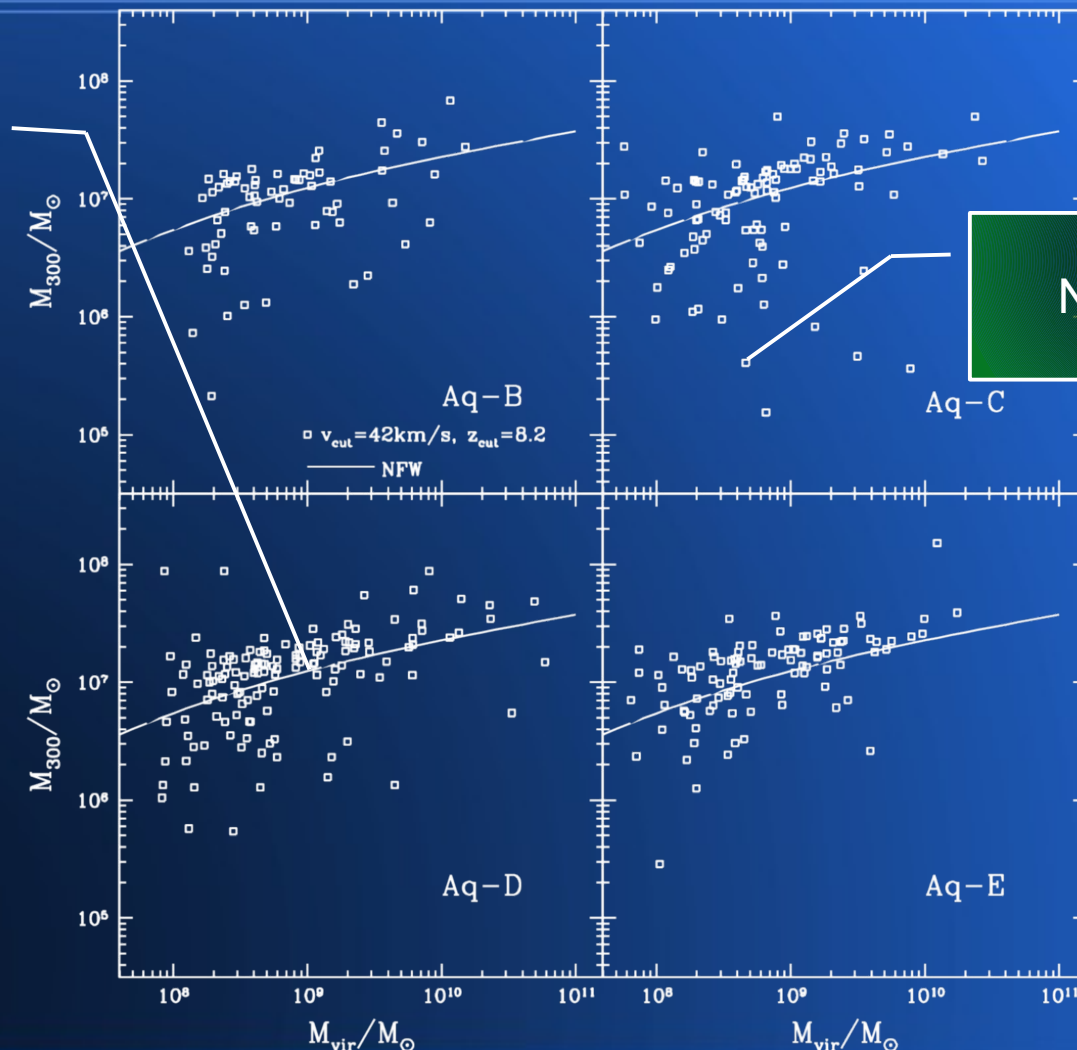
- Koposov et al. (2008) measurement
- Prediction was successful
- (Although we predicted too low surface brightness)

M_{300} of CDM Halos

Introduction | Models | Design | Applications | Decaying Dark Matter | **Local Group** | Constraints | Summary

NFW halo expectation

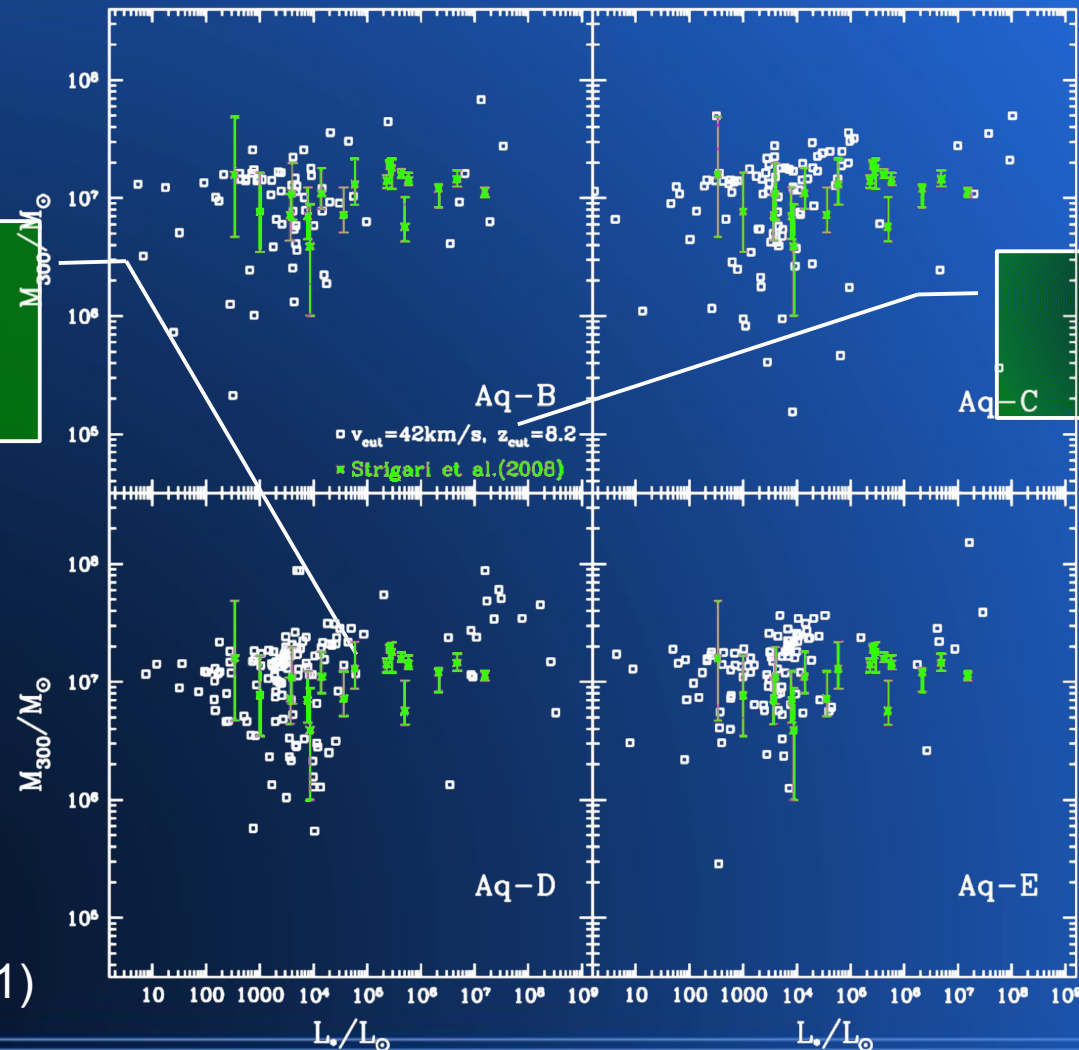
$$\rho(r) \propto \frac{1}{(r/r_s)(1+r/r_s)^2}$$



Font, AJB et al. (2011)

M_{300} vs. Galaxy Luminosity

Introduction | Models | Design | Applications | Decaying Dark Matter | **Local Group** | Constraints | Summary



Font, AJB et al. (2011)

Decaying Dark Matter Model

Introduction | Models | Design | Applications | Decaying Dark Matter | Local Group | **Constraints** | Summary



Model characterized
by two parameters

- Dark matter particle X decays to Y plus effectively massless ζ
- All are non-interacting
- May arise in inelastic dark matter scenarios.
- $M_Y = M_X(1 - \epsilon)$
- $\epsilon \ll 1$
- Y gets non-relativistic kick $v_k \approx \epsilon c$
- Decay time is τ
- Expect significant effects in dark matter halos with $v_{\text{vir}} < v_k$ and for $\tau < t_H$

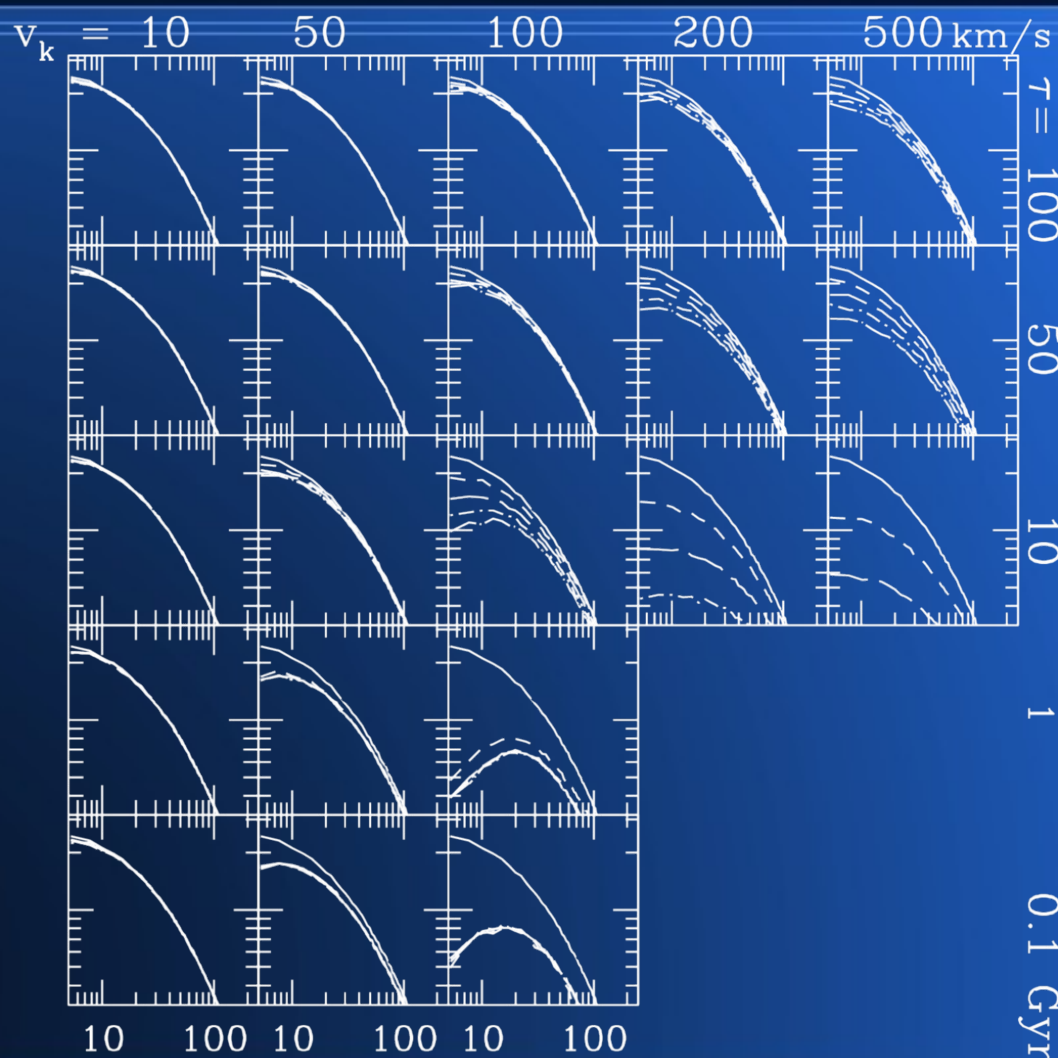
Effects on DM Density Profile

Introduction | Models | Design | Applications | Decaying Dark Matter | Local Group | **Constraints** | Summary

Density
profile

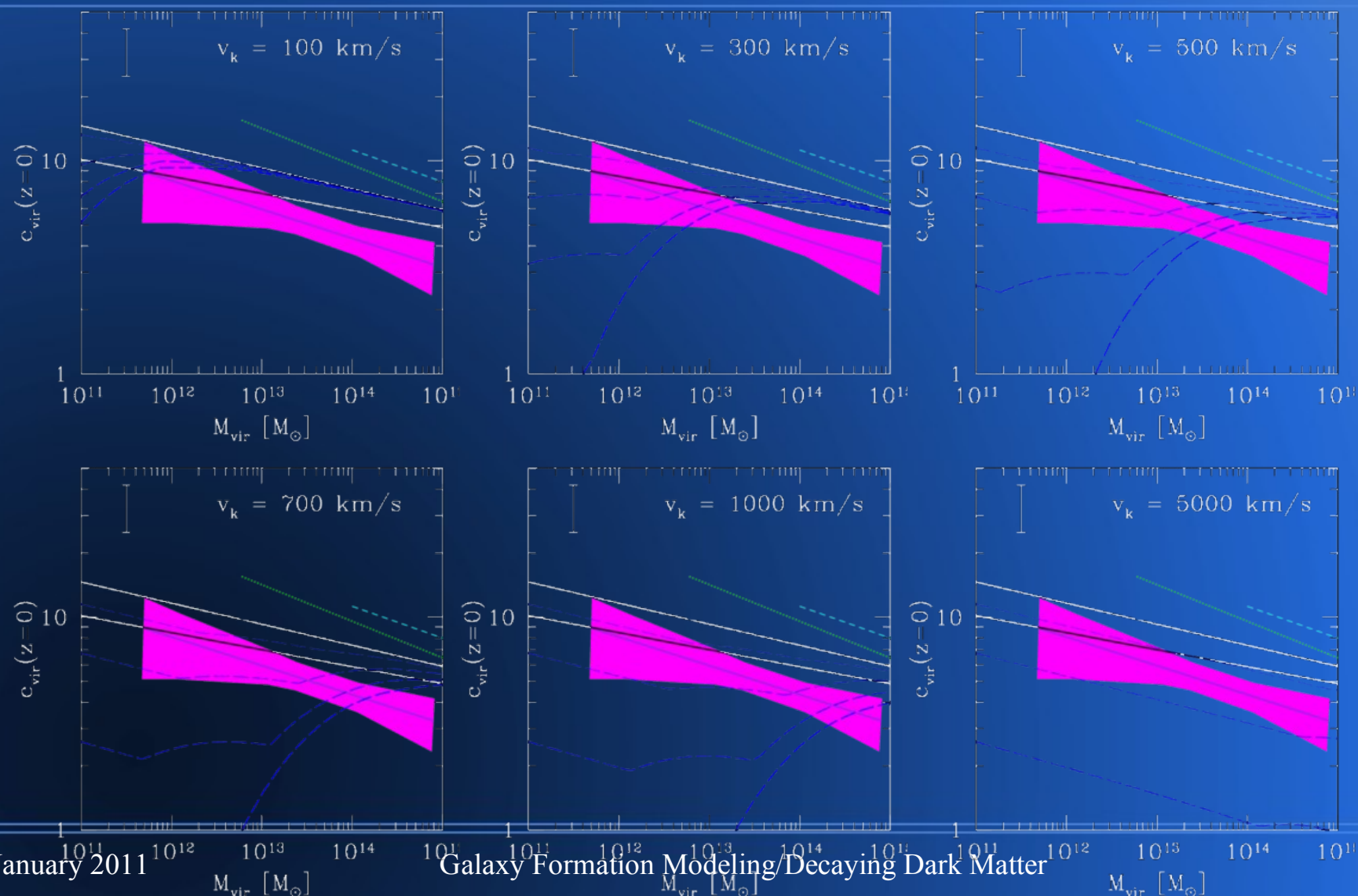
$V_{\text{vir}} = 200 \text{ km/s}$

0.0 Gyr
2.5 Gyr
5.0 Gyr
7.5 Gyr
10.0 Gyr



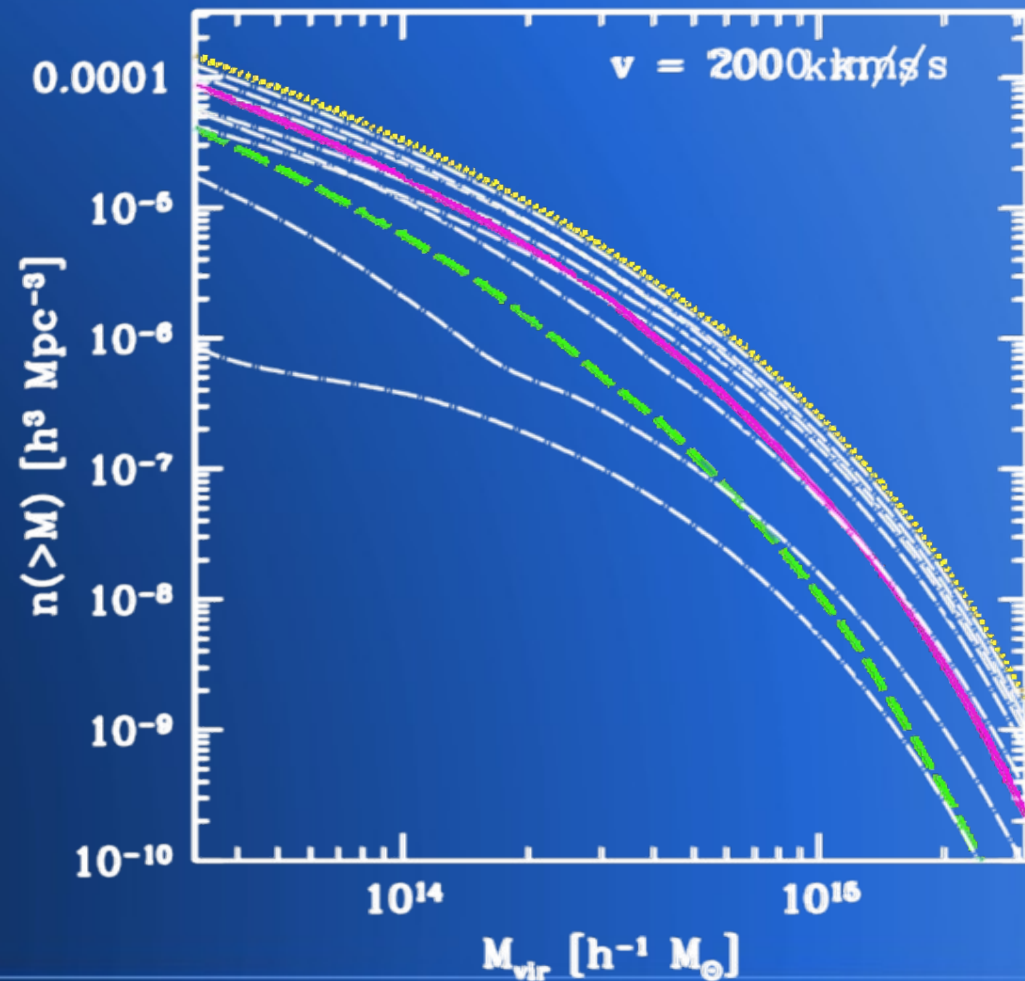
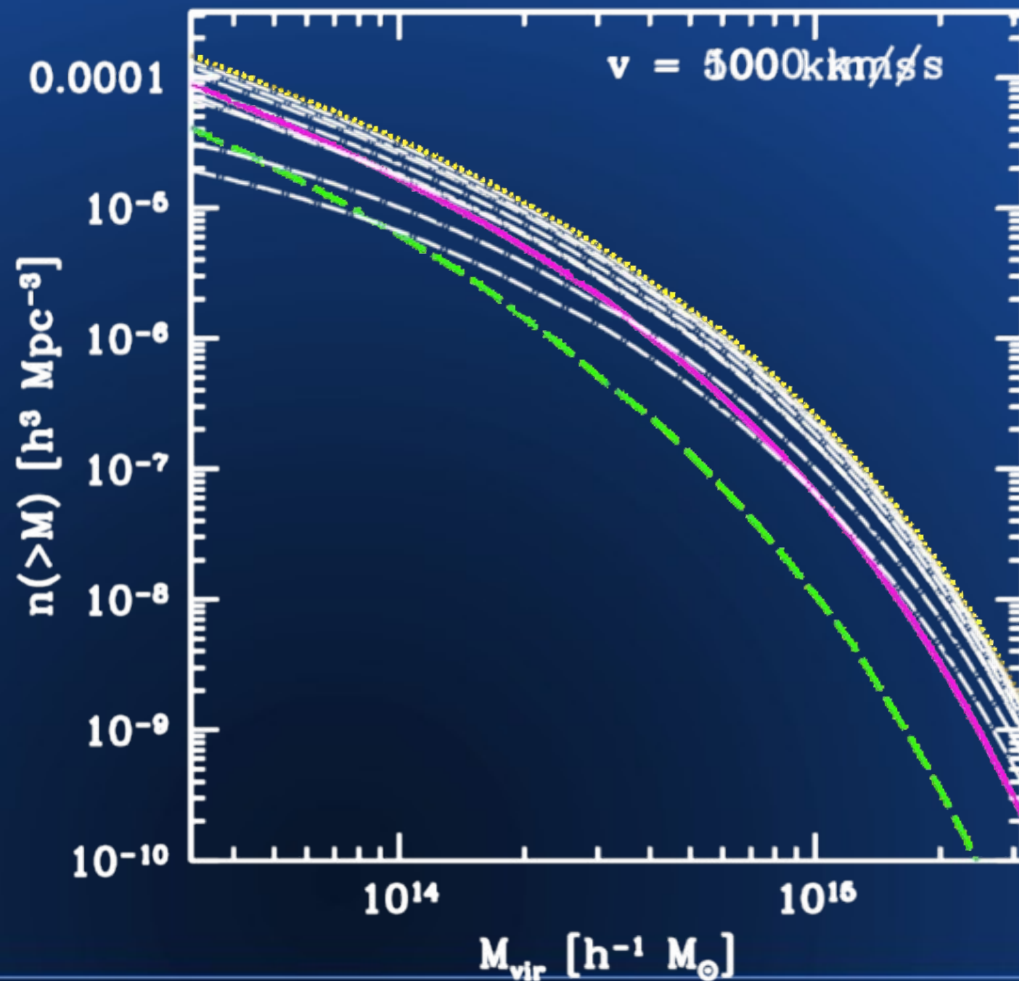
Concentrations Constraints

Introduction | Models | Design | Applications | Decaying Dark Matter | Local Group | **Constraints** | Summary



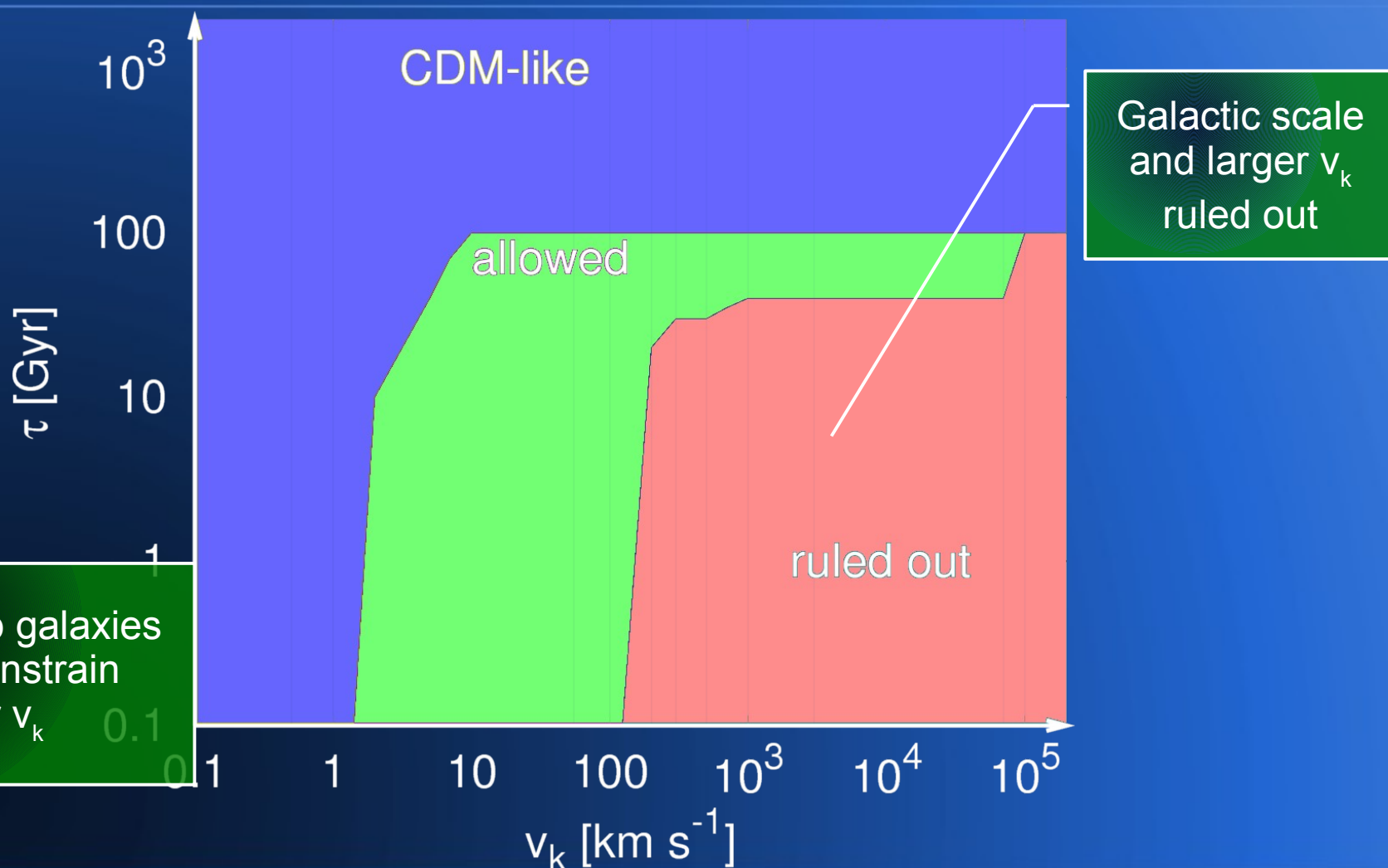
Cluster Mass Function Constraints

Introduction | Models | Design | Applications | Decaying Dark Matter | Local Group | **Constraints** | Summary



Large Halo Constraints

Introduction | Models | Design | Applications | Decaying Dark Matter | Local Group | **Constraints** | Summary



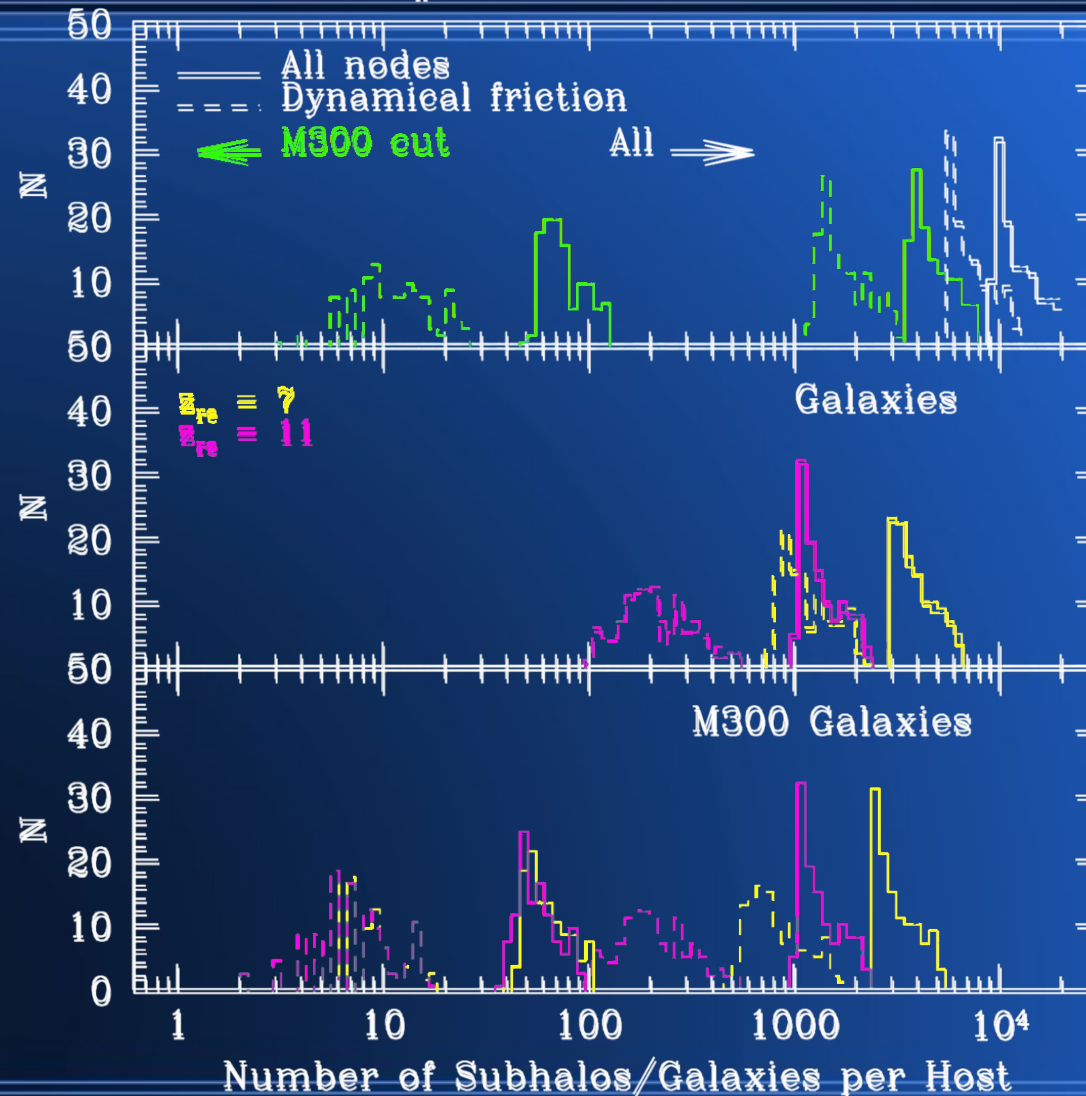
Modeling Local Group Galaxies

Introduction | Models | Design | Applications | Decaying Dark Matter | Local Group | **Constraints** | Summary

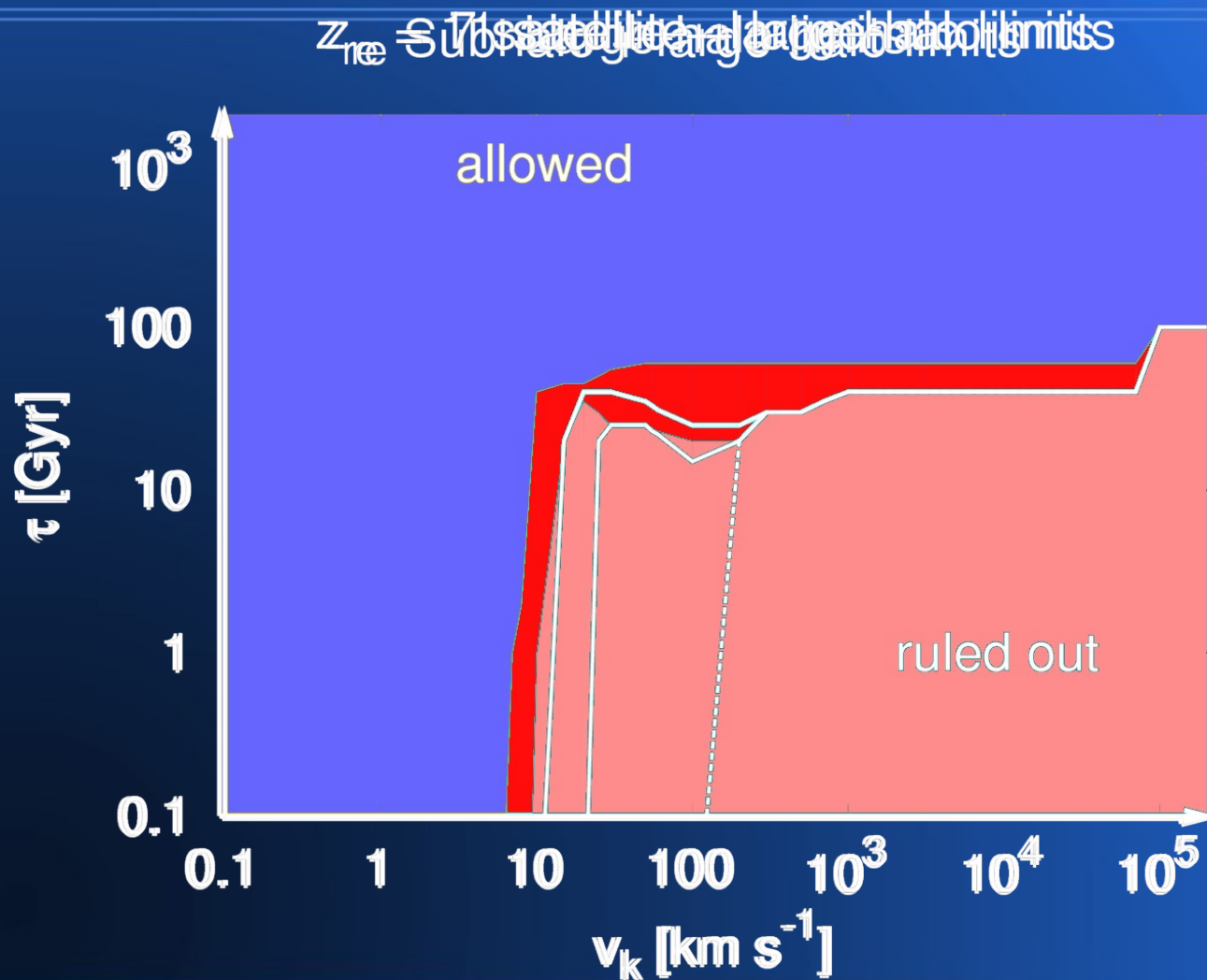
- Consider very conservative models
- Case 1: No dynamical friction
 - Maximal number of subhalos
- Case 2: Includes dynamical friction
 - More realistic, but more uncertain
- Any subhalo that forms stars is considered to be visible
- Truncate star formation in small halos after reionization

Number of Local Group Galaxies

Introduction | Models | Design | Applications | Devolving Dark Matter | Local Group | **Constraints** | Summary



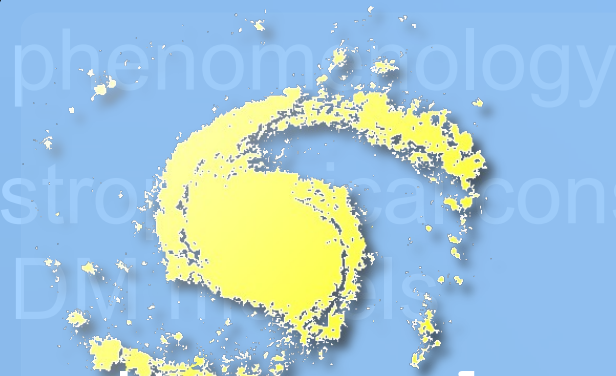
Constraints on Model Parameters



Summary

Introduction | Models | Design | Applications | Decaying Dark Matter | Local Group | Constraints | **Summary**

- Dark matter may be a standard WIMP...
- ...but it could have much richer



GALACTICUS

- Astrophysical constraints are able to constrain
- sites.google.com/site/galacticusmodel
- Key is careful/conservative treatment of galaxy physics
- GALACTICUS: complete semi-analytic model, easily modifiable.